

Pres at AIAA Electric  
Propulsion Conference  
Colorado Springs, Colo  
March 12, 1963

FACILITY FORM 002

N65-88635  
(ACCESSION NUMBER)  
28  
(PAGES)  
TMX-57505  
(NASA CR OR TMX OR AD NUMBER)

(THRU)

(CODE)

(CATEGORY)

## A VIEWPOINT ON THE FUTURE OF ELECTRIC PROPULSION

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E-2123

Good morning, ladies and gentlemen! When Professor Seifert called me by phone to ask if I would have lunch with you, I was, of course, delighted and honored to do so. I had hardly said yes, however, when he wanted a title for the talk in order to meet an urgent notice publication deadline. I am not accustomed to having talks prepared for instant use, so the title "A Viewpoint on the Future of Electric Propulsion" may have been too hasty to adequately represent material that had not yet been prepared. It was, however, satisfactory to the publication department, which caters to the topic tasters in hopes to whet your appetite for this luncheon.

A minister friend of mine recently gave a sermon on the subject of church attendance. He pointed out there are some people who only enter the church three times in their lives -- for hatching, matching, and dispatching. On these three occasions, they are doused with water, rice and dust. These three events are, of course, also of greatest significance to those who faithfully attend church every week.

Science, too, inspires in some a dedication almost as profound as the zealot, with the principles of truth, creativity, progress, and exploration of the frontiers of knowledge as the guiding creed for living. And each time a new or creative thought arises, it must follow a fairly typical life history.

First of all, when a new idea is born - **THE HATCHING STAGE** - it is met with rebuff and criticism from the well meaning but conventional thinking co-workers of the originator. If the originator loses confidence or fears this criticism too greatly, the idea may die. Just as in our three great events, this is the stage when the originator is doused with cold water.

The second is **THE MATCHING STAGE**. The rice - or seeds of truth have been planted - the idea grows until the marriage with the natural requirements is complete. The ability of the idea to explain observed phenomena or to compete with other approaches is studied. And if it can offer better performance or insights than competitive schemes, a winner has been obtained. Engineering developments might follow. Or contrarywise, if it can not meet the competition it is dispatched to the morgue of unreferenced publications. Anywhere along the line from hatching to dispatching, there may be peaks and valleys of enthusiasm or despondency, confidence or disenchantment. These responses may and often are closely tuned to advancements in related fields.

Of course, there are a few dedicated enthusiasts such as yourselves who never lose confidence (and this is sometimes fortunate) who, like the proverbial ostrich that buries his head in the sands of hopefulness - sees not the destructive influences which may send his project to the graveyard.

Electric propulsion has certainly been through several cycles of hope and despair. I believe we, at the Lewis Research Center, have been in a favorable position to follow these cycles of progress, admittedly sometimes with our eyes closed to the apparent facts.

Our efforts began with a few lectures and a few studies on electric propulsion in 1956. Our first space environment had no meteoroids. We glibly assumed that hot radiators or nuclear radiations would not inconvenience the payload and other ship components. We naively assumed that our electric spaceship could have greater reliability with lighter weight components than had ever been achieved on the ground. And this large ship with 1/2-acre radiators could be launched into orbit, somehow. Thus we idealized the problem to determine how interesting electric propulsion might be under optimistic conditions. I think the periods of pessimism that inevitably follow result each time one faces reality in each of these idealized assumptions. Nevertheless, our calculations did suggest that electric propulsion was feasible under ambitious circumstances.

Relative to other propulsion means, electric propulsion systems are very heavy. This is another way of saying that the thrust to weight ratios are very low. The rate of fuel consumption, however, is also low so that long time highly energetic missions which would require inordinately high fuel loads by conventional means can be expeditiously accomplished with greater payloads by electric propulsion. In other words, the increased powerplant weight is hopefully more than compensated by the decreased initial fuel load. Of course, the more energetic the mission requirements, the higher will be the desired jet velocity or specific impulse. This is due to the trade-off between fuel load and powerplant weight.

For near earth missions, the best specific impulse is low - say less than perhaps 2000. These near earth missions are not very interesting by electric propulsion. This conclusion follows from a consideration of the powerplant which, for this argument, will be nuclear powered. Reactor heat is converted to electricity by direct or indirect means at no more than 20% efficiency. Hence, at least four times the required power must be radiated to space in a radiator that is both heavy and cumbersome. It also is sensitive because of its large area to meteoroid damage. Electric propulsion would therefore not be competitive, in general, with a developed and dependable open-cycle nuclear rocket in the range of specific impulses up to perhaps 2000 seconds.

To my mind, the arc jet falls in this category, having a specific impulse of only about 1500 seconds at best. I thus generate my first wave of enmities in this audience by saying that the arc jet is not interesting for space propulsion.

Inasmuch as this is the first of several general conclusions to be presented, let me clarify my meaning. The arc jet can clearly accomplish a few missions better (i. e., cheaper) than other propulsion systems. Among these are near earth missions raising large satellites to higher orbits when the electric power system is already on board. This mission, however, can be accomplished by other soon to be available means. On the other hand, the arc jet does not offer any great potential for high energy missions. Hence, the role it will play in space propulsion is a relatively minor one. Thus my general conclusions can be correct in the broader sense, but wrong in detail.

In our early studies of electric propulsion, we devoted about equal efforts to the accelerators and to the power generation system problems. We guessed that the accelerator would be the easier problem but we were not sure. There was a wealth of information on ion sources but none of them had demonstrated the combinations of high current densities, propellant utilization fraction, and high efficiency that is desired. We therefore put enough effort on accelerators to convince ourselves, at least, that accelerators could be built to give the required performance.

There is a lot of work to do yet. We need higher efficiencies and higher propellant utilization fractions, and certainly a lot more endurance. But the combined efforts of the Lewis Research Center, the Electro Optical Systems Corporation, Hughes Tool Corporation, Space Technology Laboratories and elsewhere have certainly convinced most of us that the accelerator business is much farther along than the power generation systems. Furthermore, I believe most of us are convinced by now that charge neutralization of the ion beam will cause no serious problems. Thus, I arrive at my second conclusion. Much more effort should now be devoted to lightweight dependable space power systems than to the accelerators. The power production system is much more likely to delay the practical use of electric propulsion than would the accelerator.

The two keynote problems of the power generation system at present are (1) to achieve a sufficiently light powerplant and (2) to achieve sufficient endurance. An indication of these problems is shown on Slide 1 where electric propulsion is compared with the nuclear rocket for a manned Mars mission. Clearly, the powerplant specific weights should be less than about 20#/kw and reliability should be proven for times on the order of 500 or 600 days. The intersection of the nuclear rocket curve with those of powerplant specific weight generates in itself a curve similar to that shown on Slide 2. These two figures utilized different mission assumptions so there is only qualitative agreement between them.

There are presented here (Slide 2) several missions. On each of them, the powerplant specific weight must be lower for a given trip time than the presented curve if electric propulsion is to exceed the capabilities of the nuclear rocket. Even though there is no universal curve, it is clear that longer trip times permit higher specific powerplant weights. However, the reliability requirements become more extreme. Now, one can imagine that reliability could improve if powerplant weight is allowed to increase. One could then superimpose a curve of endurance time on this one as a function of powerplant weight. The optimism for electric propulsion then is described by these limiting curves. If the powerplant specific weight is too high or the endurance is too poor, then electric propulsion would lose its competitive status.

Let us dwell for a moment on this question of endurance. One year has about 8800 hours so we are asking for at least 10,000 hours of trouble-free operation. An automobile would travel 300,000 miles at 30 miles an hour in that time. Surely some trouble would be expected. So our space powerplant must be much better than our automobile. No one knows how reliable a space powerplant can be, but the longest running time so far has been a factor of about 20 too low. Here is a place where I close my eyes to the facts and assume that if we can get a system to run a few hundred hours with reliability, that perhaps with ingenuity, longer times can be achieved. So let's consider the other problem - that of obtaining low specific weights.

The heaviest component of an electrical power generating system is the radiator for eliminating the waste heat. It is also the most vulnerable to meteoroid damage. The radiator for a 10 megawatt system might weigh four or five pounds per kilowatt if it did not have meteoroid protection. With protection, the weight could easily be 20 or 30 lbs. per kilowatt for the long time missions. Because the area of the radiator is strongly temperature dependent, there is a strong temptation to run the system at the highest possible temperature to reduce radiator area and hence, system weight. The limiting temperature is set by material corrosion difficulties in proposed Rankine cycle liquid metal systems. High temperatures imply refractory metal loops that must be developed in an oxygen-free environment. So the problems are not easy.

The possibilities of using light weight material might raise the question of how high one should increase the radiator temperature. A beryllium radiator, for example, could feasibly be operated at 1400°F. Beryllium is one-fourth as heavy as conventional high-temperature materials. Thus a "conventional" high-temperature radiator would have to operate quite a bit hotter to break even with beryllium on a weight basis. Beryllium, on the other hand, may have unacceptable fabrication problems. Or perhaps the radiator tubes might shatter under meteoroid impact, or launch vibration conditions. So the beryllium radiator is still speculative.

On a two phase Rankine cycle system schematically diagrammed on Slide 3, the metal vapor from the turbine passes into the radiator where it is condensed. Hence, the radiator is maintained throughout at nearly the maximum inlet temperature by the two phase condensing process.

For the Brayton cycle or all gas system, Slide 4, there is inherently a large temperature drop across the radiator. Hence, the radiator for the Brayton cycle must be considerably larger for a given inlet temperature. For this reason, using the meteoroid frequency and penetration relations of a few months ago, the Brayton cycle was thrown out for electric propulsion as being too heavy.

But now suddenly we have a new miracle of optimism in the form of meteoroid damage data from the Explorer XVI satellite. This data has only recently been evaluated. Slide 5 shows the number of penetrations per square foot per day as a function of stainless steel thickness. This curve is a modification of information contained in the recently released TMX-810, February 1963, compiled by Carl C. Hastings, Jr. You can see that the Explorer XVI data is about an order of magnitude lower in the number of penetrations than you would have estimated by Whipple's 1961 flux data and the Bjork penetration criterion. These two assumptions have been commonly used in the literature to arrive at long lasting engineering decisions. I wish to caution you that the data were obtained only for penetrations through a few thousandths inches

of material. Extrapolation to material thicknesses of perhaps 1/4 inch may be risky. Nevertheless, I am going to be optimistic and assume that the extrapolation will be verified.

This new Explorer XVI data has a profound influence on the whole question of space power. One obvious conclusion is that the previously designed radiators would last ten times as long in the new meteoroid damage space. Or alternatively, a redesigned radiator having the former survival probability will be lighter in its protection armor by about a factor of 2. This, in turn, increases the optimism in the ultimate success of electric propulsion systems. Thus, Conclusion III - the probability that light weight dependable space power systems can be built is considerably higher than it was six months ago. Hence, electric propulsion is considerably more interesting now than it was then.

Correspondingly, many of the engineering conclusions that we had formerly drawn must be re-evaluated to ascertain their present correctness. For example, we had all but discarded the Brayton cycle as being too heavy for electric propulsion. This left us with many real tough engineering problems associated with the Rankine cycle liquid metal system. Among these might be listed the liquid metal erosion and corrosion problems, with sludging and radiator clogging associated with material transfer; the difficulties associated with obtaining reliable turbine materials, and bearings, and seals; with condensation problems

in the turbine, and the turbine exhaust moisture content, with condensation and fluid distribution problems in the radiator under zero "g" conditions, and with probable restart difficulties. Some of these would have to be evaluated by costly flight experiments in space.

Many of these difficult engineering problems associated with two-phase liquid metal systems can be avoided by utilizing the all gas Brayton cycle. This might now be feasible with the new meteoroid damage statistics. Using an inert gas such as Neon or Argon, most of the corrosion problems vanish. Hence, higher temperatures can perhaps be utilized in the cycle. The unit could be canned, thus eliminating the problem of seals on the alternator. The use of gas bearings might lead to a system with almost indefinitely long time reliability. What's more, we have a great deal of experience with Brayton cycle machinery from our studies of the turbojet engine. I thus propose Conclusion IV - namely that the Brayton cycle should be carefully reexamined as a potential power source for electric propulsion systems.

The radiator has been the key to these changed outlooks with the new meteoroid damage data. I would perhaps be remiss if I did not look at the unconventional radiators. Slide 6 shows to the left and center the so-called belt radiators. The first is the one proposed by Weatherston of the Cornell Aeronautical Laboratory. The primary heat transfer cylinder rotates on this arrangement. On the second or Rocketdyne proposal, the belt progresses caterpillar fashion around the stationary cylinder.

Under the outgassing high vacuum conditions of space, one of the major heat transfer mechanisms - that of the thin convection gas film between belt and cylinder - may be lost. In order to evaluate this possibility, Messrs. R.D. Sommers and W. D. Coles have conducted studies at the Lewis Research Center on the heat transfer between two surfaces in contact under soaked vacuum conditions ( $10^{-6}$  mm). These data are shown on Slide 7. The heat transfer here is a factor of 20 - too low to be usable in a space radiator system. Additional data using molybdenum on stainless steel were a factor of four lower than these values. One might be able to coat the surface of the belt with liquid tin or gallium to increase the heat transfer to a usable value and we are conducting experiments to determine the effectiveness of the idea. Our calculations, however, suggest that the evaporation rate of the liquid tin might be too high in space. Also, with the new meteoroid data, the prestige of conventional tube and fin radiators has been raised relative to that of the belt radiators. Hence, Conclusion V follows that the belt radiator is no longer of interest for space power systems.

Weatherston's radiation amplifier shown in Slide 8 is not necessarily ruled out in this conclusion. Some of us at Lewis are still interested in the radiation amplifier but using belts of spherically shaped shells rather than disks.

When we come to practical systems, some redundancy will certainly be required to achieve reliability. This is my Conclusion VI. In the space radiator, this redundancy can be achieved by segmentation. The idealized weight advantage associated with segmentation is shown in Slide 9 as a function of the number of segments. Segmentation holds a further advantage in that the power-generation system may continue to operate at a reduced power level after being damaged. For this particular example, the reduced radiator effectiveness is limited to 0.75 of the original capacity. Radiator segmentation should be used providing the weight penalty is not too great.

Some discussion should be included on the status of thermionic-converter space power systems. The thermionic converter boils off electrons from the emitter, which then progress to the collector (Slide 10). In this manner, heat is directly converted to electricity by differences in temperature and work function between the emitter and the collector.

The power level of the vacuum thermionic converter is, of course, space-charge limited. Therefore, if reasonable spacing between cathode and anode are employed, an easily ionized gas such as cesium must be inserted to neutralize the electronic charge. The resulting "plasma thermionic converter" has received considerable interest as a potential source of space power.

The theoretical Carnot efficiency of the plasma thermionic converter ranges from 25 to 50 percent. Experimental efficiencies have been about one-third, or perhaps recently to one-half of these values, or a maximum of about 17 percent. The remaining heat energy must be discharged to space by means of a radiator. Unfortunately, the higher efficiency occurs with the lowest anode temperature which suggests a larger radiator. When the system weight including the radiator is minimized, the efficiency is approximately 10 percent, or perhaps a little higher with the new meteoroid data.

When we decide to use the thermionic converter in a space power system, we must decide whether to install the elements in pile or in an out of pile arrangement. The out of pile design is much easier and straight-forward. A liquid metal or gas loop would carry reactor heat to the individual cathodes. However, the limiting temperature of the liquid metal system occurs in the reactor with the cathode at a still lower temperature. In this arrangement, there is perhaps a 600°F penalty on the maximum cathode temperature leading to estimated system weights so large that we may draw Conclusion VII - that out of pile thermionic conversion systems are not interesting for electric propulsion at this time. The conclusion depends strongly on the maximum feasible temperature of the system. The higher the temperature, the more feasible the out of pile arrangement.

A schematic diagram of an in-pile thermionic converter system is shown on Slide 11. Perhaps ninety percent of the energy so generated must be carried to the space radiator by means of a working fluid. Because the converter is a high-temperature device, the anode cooling and the transfer of heat to the radiator are accomplished by a liquid-metal system. Hence, the thermionic converter has the same limitations on performance due to the use of liquid metals as the Rankine cycle rotating-machinery device. The thermionic converter may operate at higher temperatures - turbine inlet temperature corresponds to anode temperature - but gains from this difference are offset at present by the lower efficiencies of the minimum-weight diode system.

Studies have been conducted on the use of gaseous cooling of the anode to raise the operating temperatures. In these studies, the pumping power to circulate the cooling fluid was unreasonably large except when large temperature drops across the radiator were employed. Then the radiator became both large and, with meteoroid protection, too heavy. Hence, gas-cooled thermionic conversion systems currently are not interesting for electric propulsion.

For that matter, no one has yet designed a satisfactory liquid-cooled thermionic power system for space. One might propose a reactor composed of a critical assembly of thermionic diodes, each with its uranium-fueled cathode. The engineering problems associated

with balancing the nuclear characteristics of such a reactor with the diode thermal and electrical requirements, including the multiplicity of series and parallel groups of diodes, each cooled with a properly insulated liquid-metal system connected to a common radiator, is challenging to say the least. Add to this, the requirement for replaceability of each radioactive diode unit upon failure and the problem becomes even more difficult. When engineers are actually faced with this design job, they may find that the optimistically low estimates of the weights of the thermionic conversion systems sometimes included in the literature will grow to equal or surpass the weight estimates of more conventional approaches.

There is still another major problem with the thermionic system. It requires a relatively heavy power conditioning system to provide the proper voltage and currents for electric propulsion. When I consider the horrendous difficulties in arriving at a satisfactory engineering design for the thermionic system, I come to the conclusion that the thermionic system has to show a lot more progress before it can compete with dynamic power systems for electric propulsion.

There are many more items that could be discussed such as the use of radioisotope balloons, or solar concentrators, or thin film light weight solar cells, for that matter. However, time and my own desires preclude a further elaboration.

I would like to close, however, with the suggestion that the electric propulsion enthusiasts keep their eyes on the competitive propulsion schemes. We might as well be realistic and recognize that nearly all the near earth missions will be accomplished by chemical propulsion. The new meteoroid damage data also favors the hydrogen-oxygen rocket for proceeding farther into space. For the future, the nuclear heat transfer rocket must certainly be considered. With improved design, both multi-staging and long time reliability are feasible. Such rockets could cover large portions of solar space. Then there are schemes such as Project ORION and gaseous core reactors. These offer specific impulses in a range to be competitive with electric propulsion. They also offer - on paper - thrust to weight ratios greater than one.

On the other hand, our civilization will have an ever increasing need for light dependable space power systems. So the electric propulsion enthusiasts can be confident that their efforts in the power generation field will be valuable, irrespective of the status of competitive propulsion systems.

# MANNED MARS MISSION

CREW SHIELDING FOR 100 REM DOSE, METEOROID SHIELDING FOR  $P_0$   
 $= 0.999$

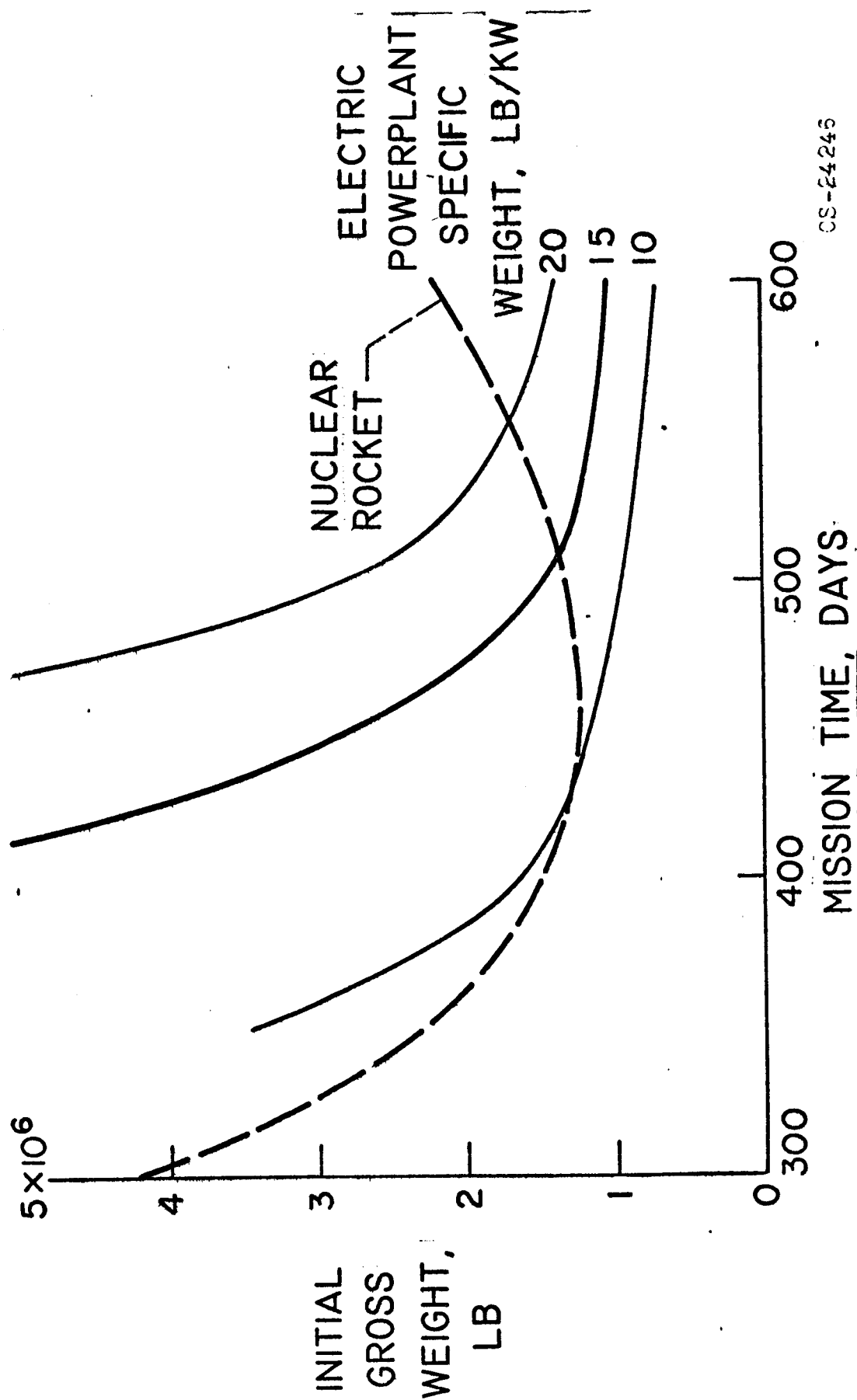
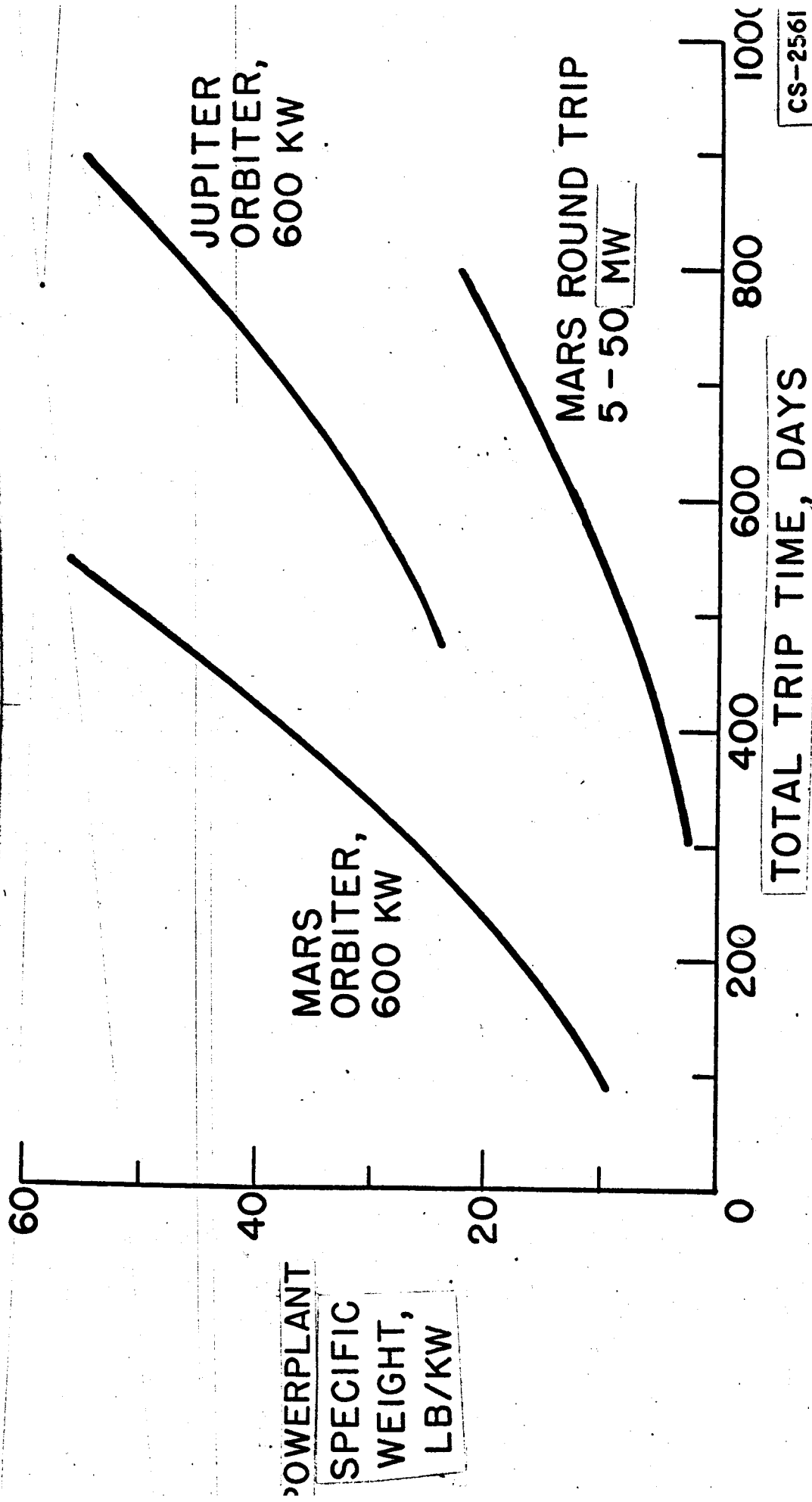


Figure 1.



CS-2561

Figure 2. - Electric powerplant specific weight for equal payload weight for nuclear rocket and electric rocket.

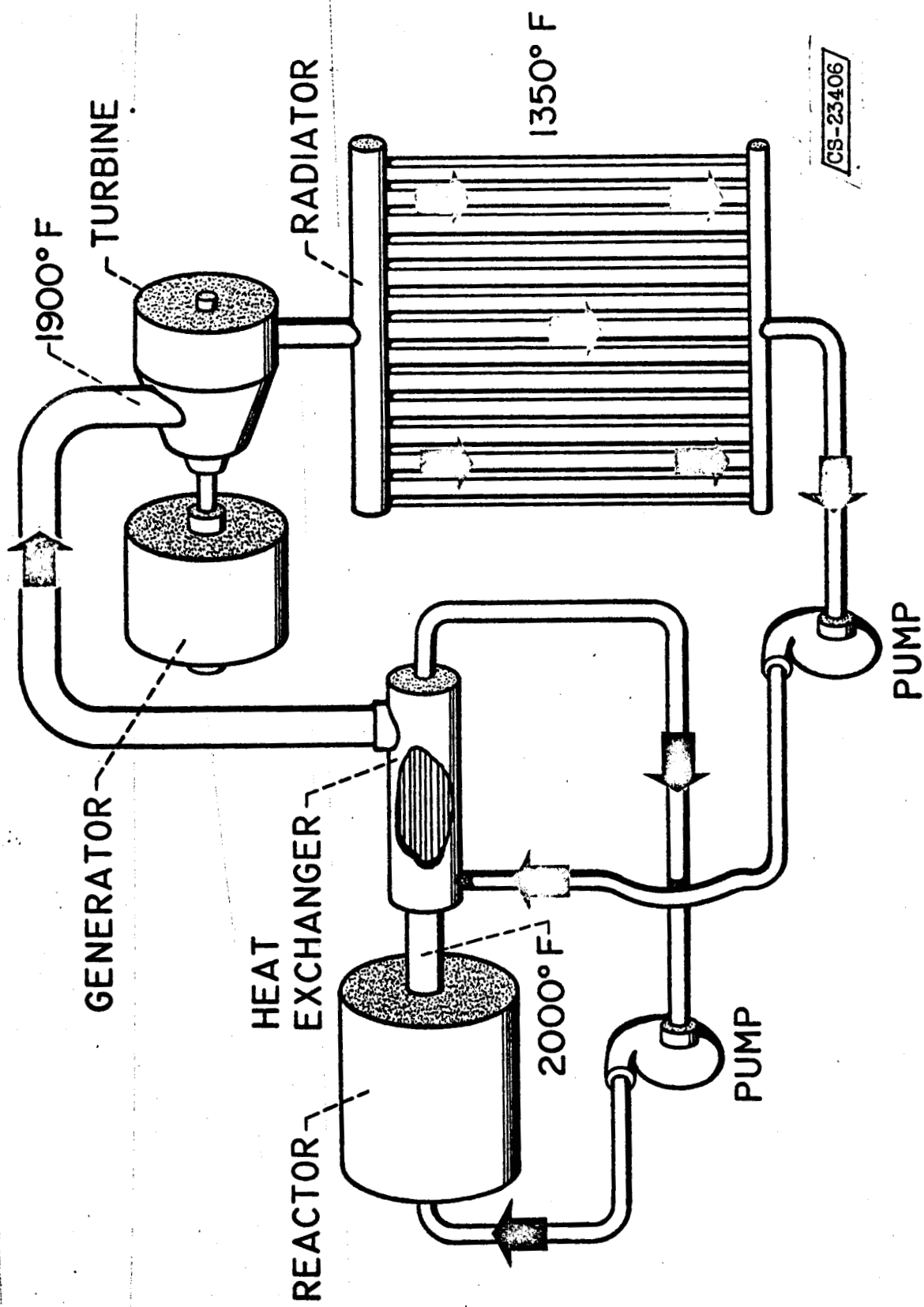
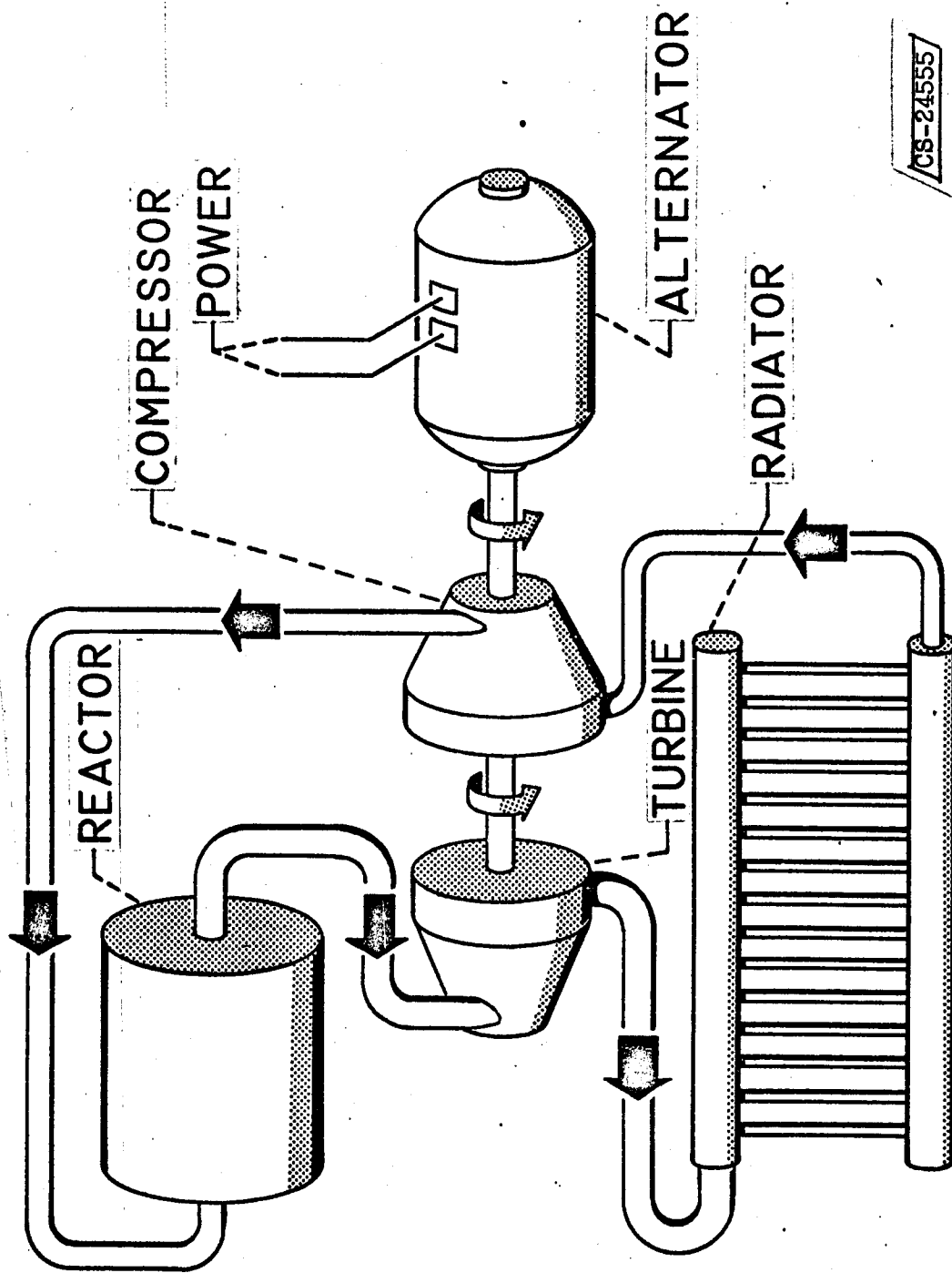


Figure 3. - Schematic of Rankine cycle space power system.



CS-24555

Figure 4. - Schematic of Brayton cycle space power system.

# METEOROID PENETRATION RATE

EXPLORER XVI DATA - JAN 13, 1963

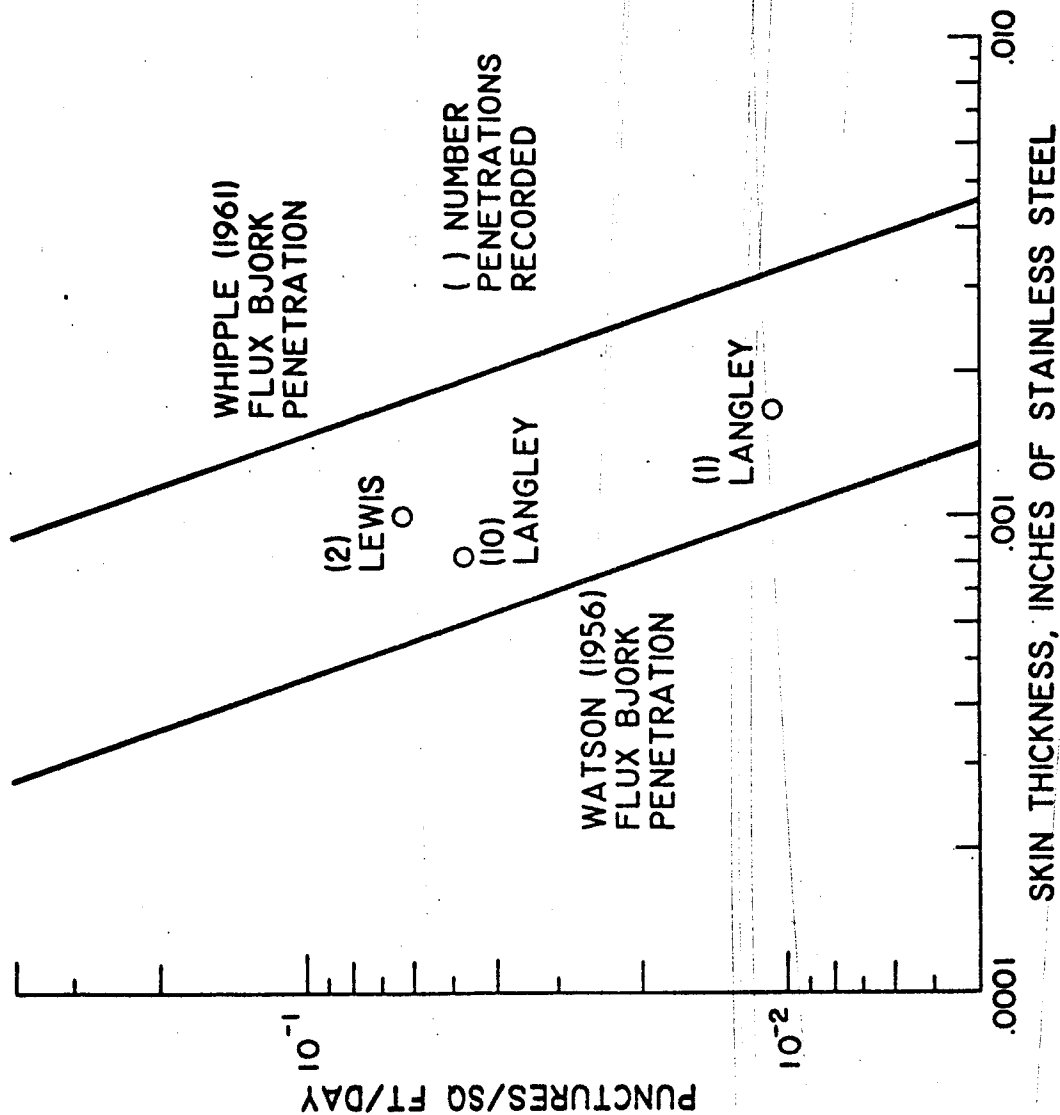


Figure 5.

# NONFLUID RADIATORS

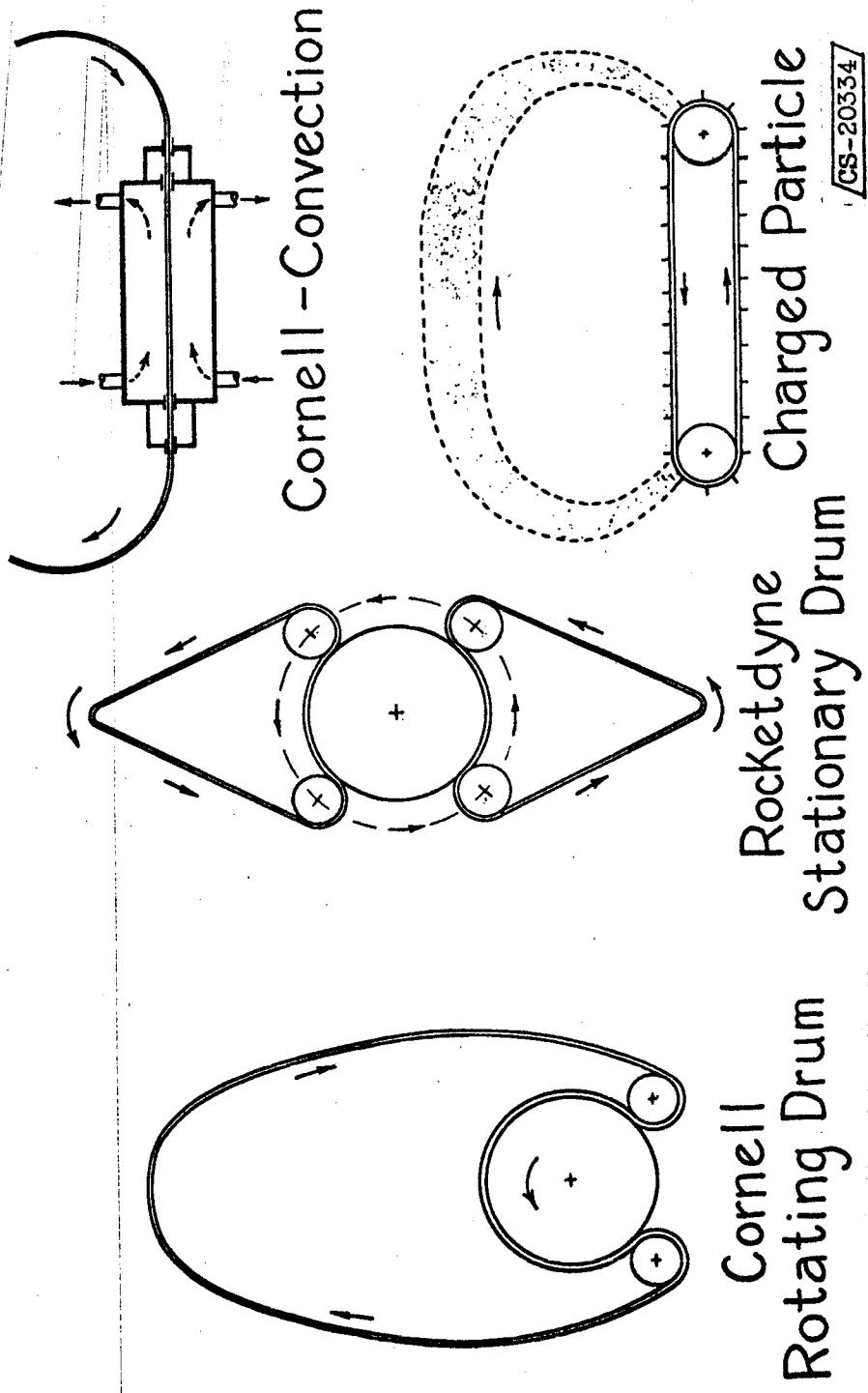


Figure 6.

CS-20334

# THERMAL CONDUCTANCE

## STAINLESS -- STAINLESS INTERFACE IN A VACUUM

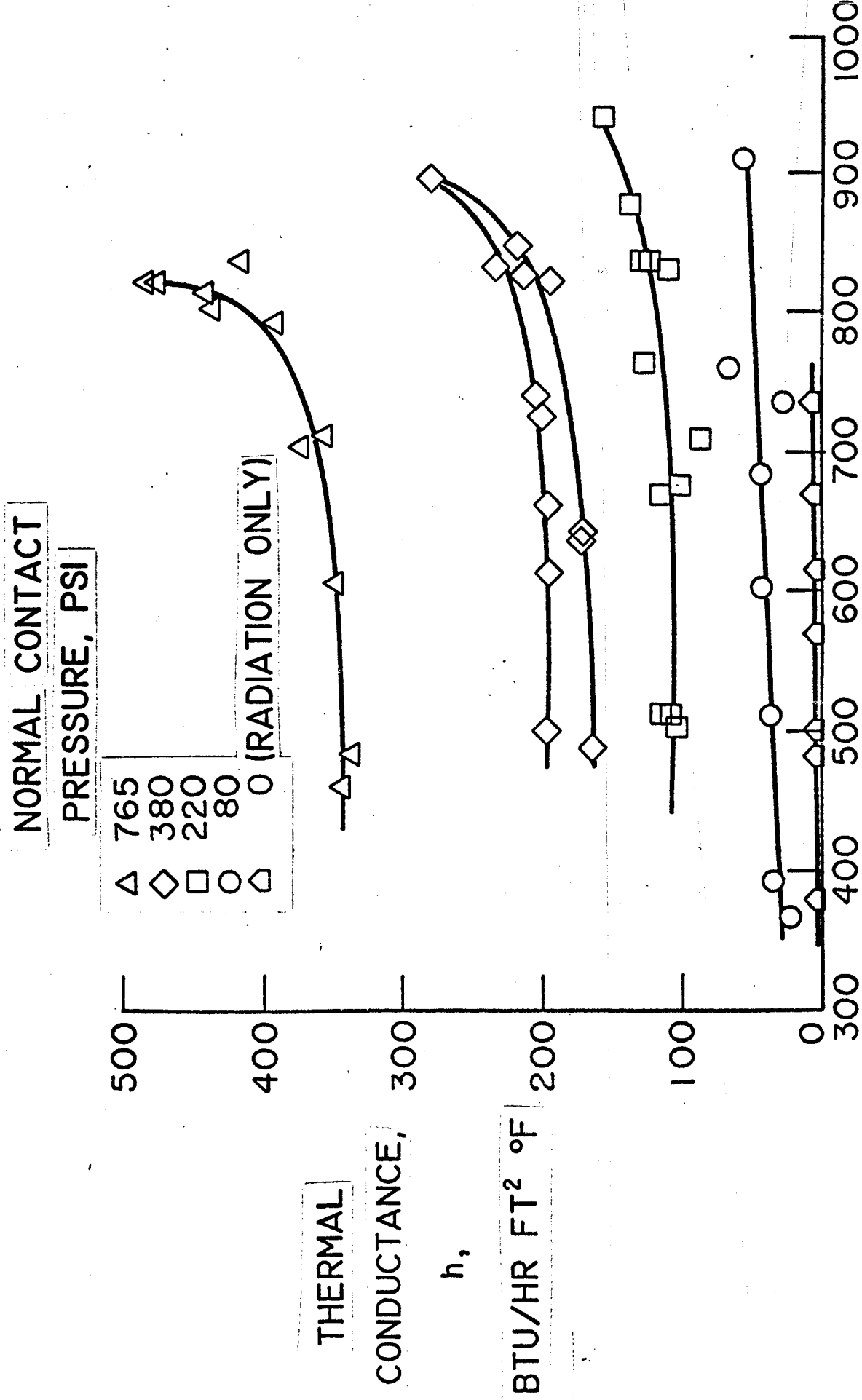
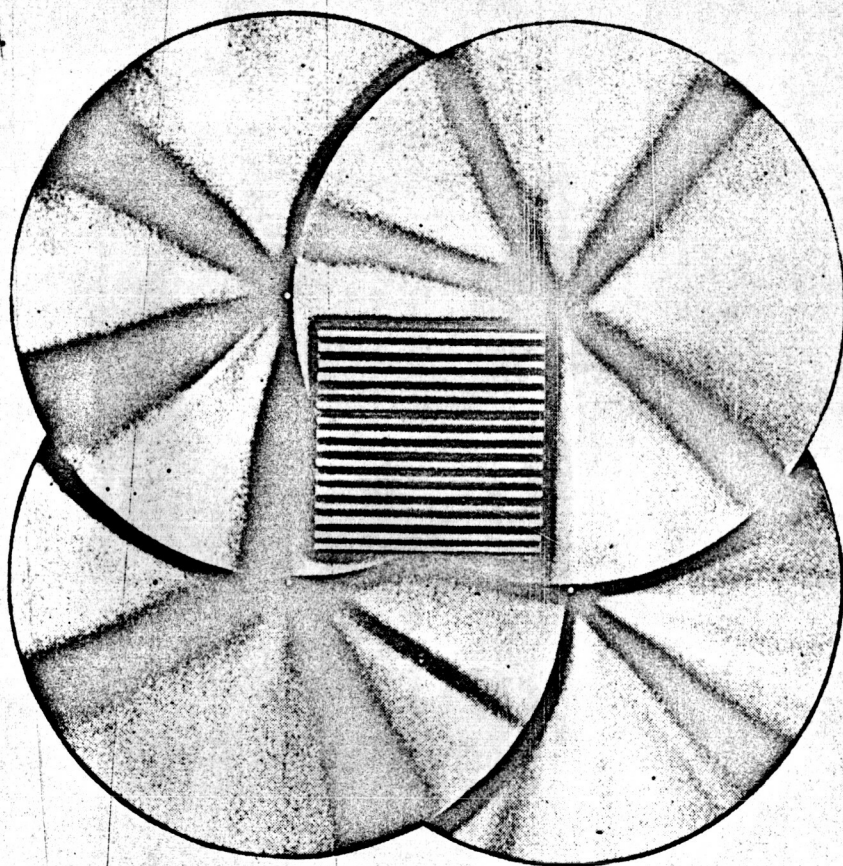


Figure 7.

# DISK TYPE RADIATION AMPLIFIER

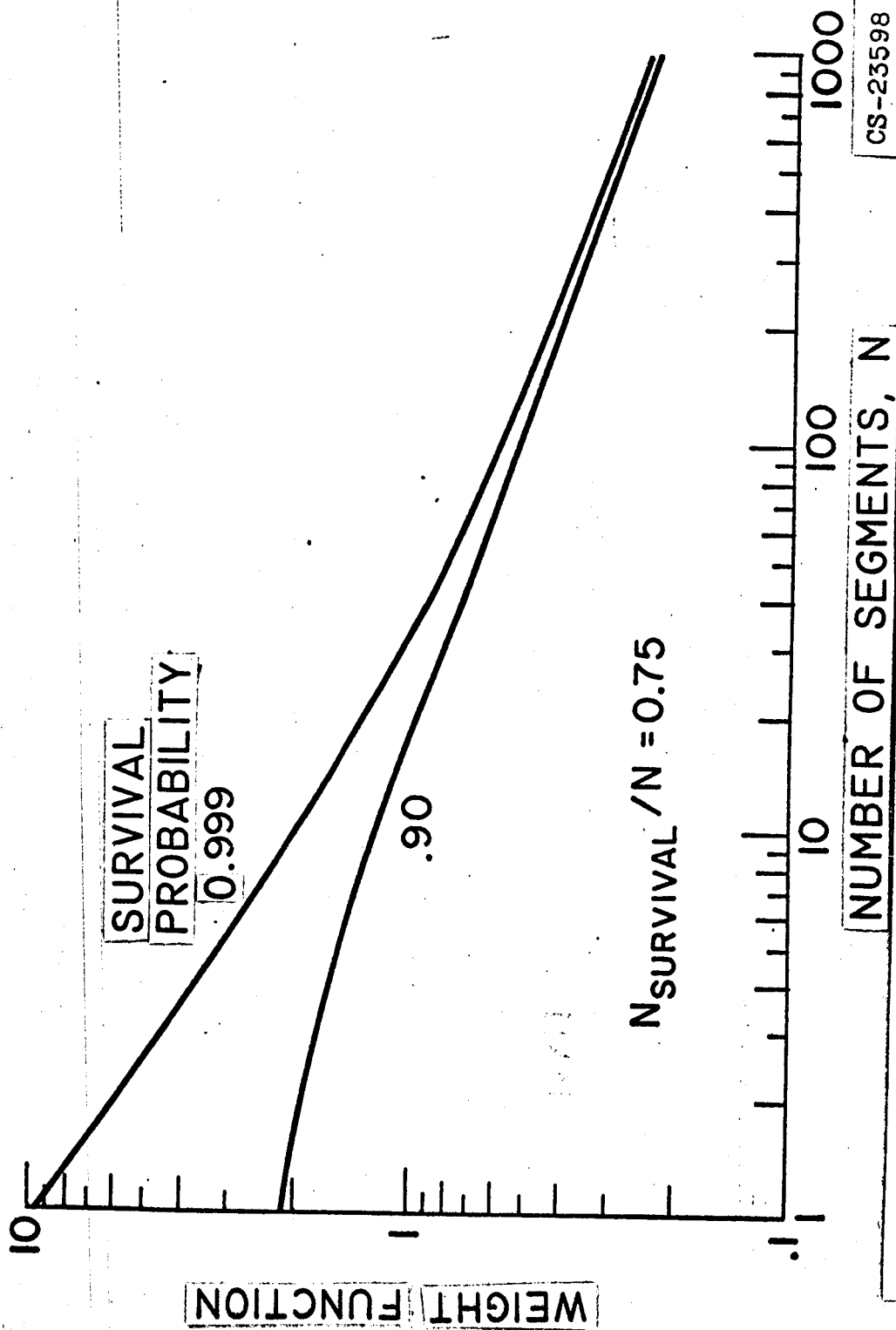


NOTE: WITH EIGHT DISKS  $f = 5$   $\gamma = .2$



Figure 8.

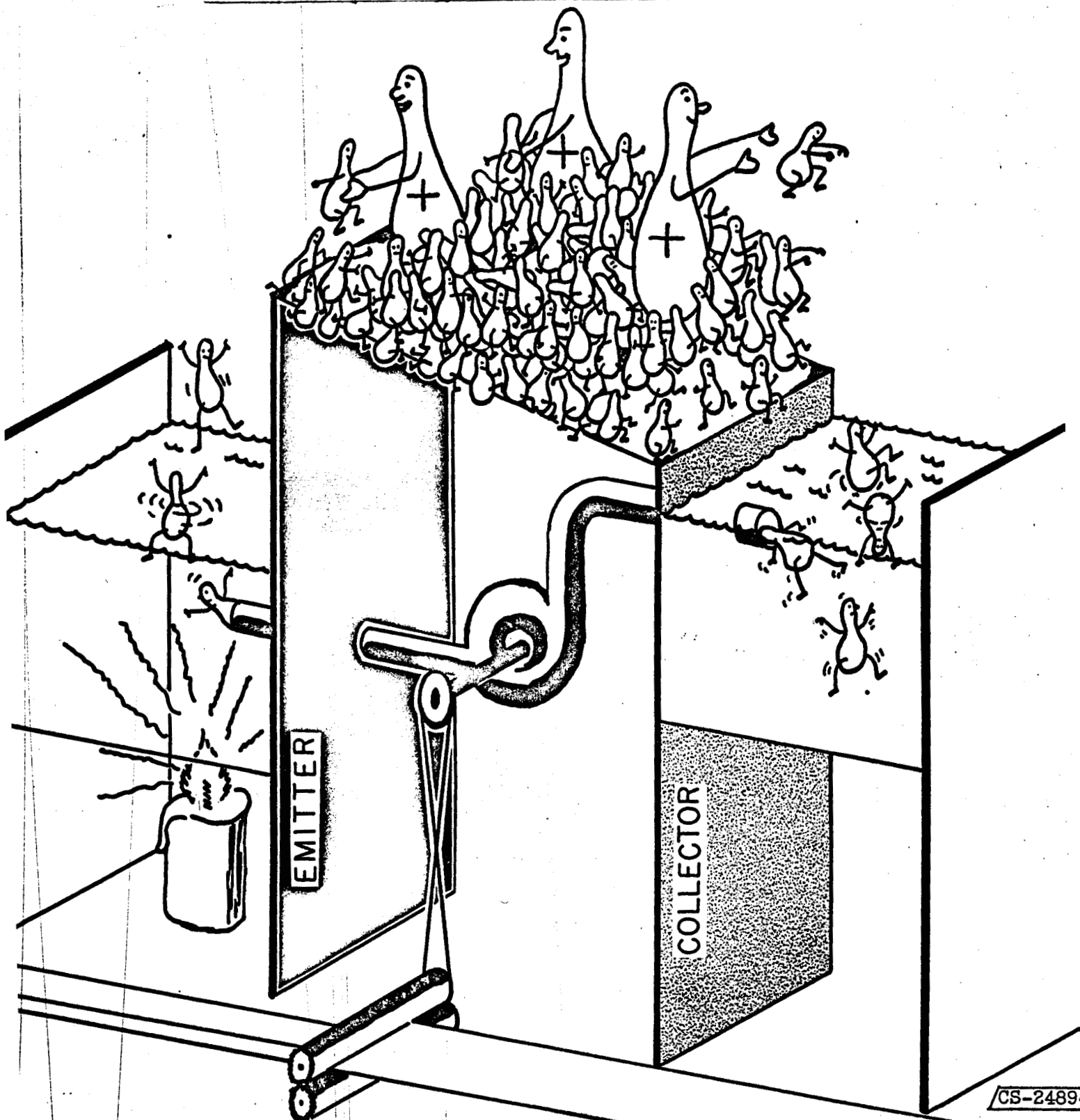
CS-24891



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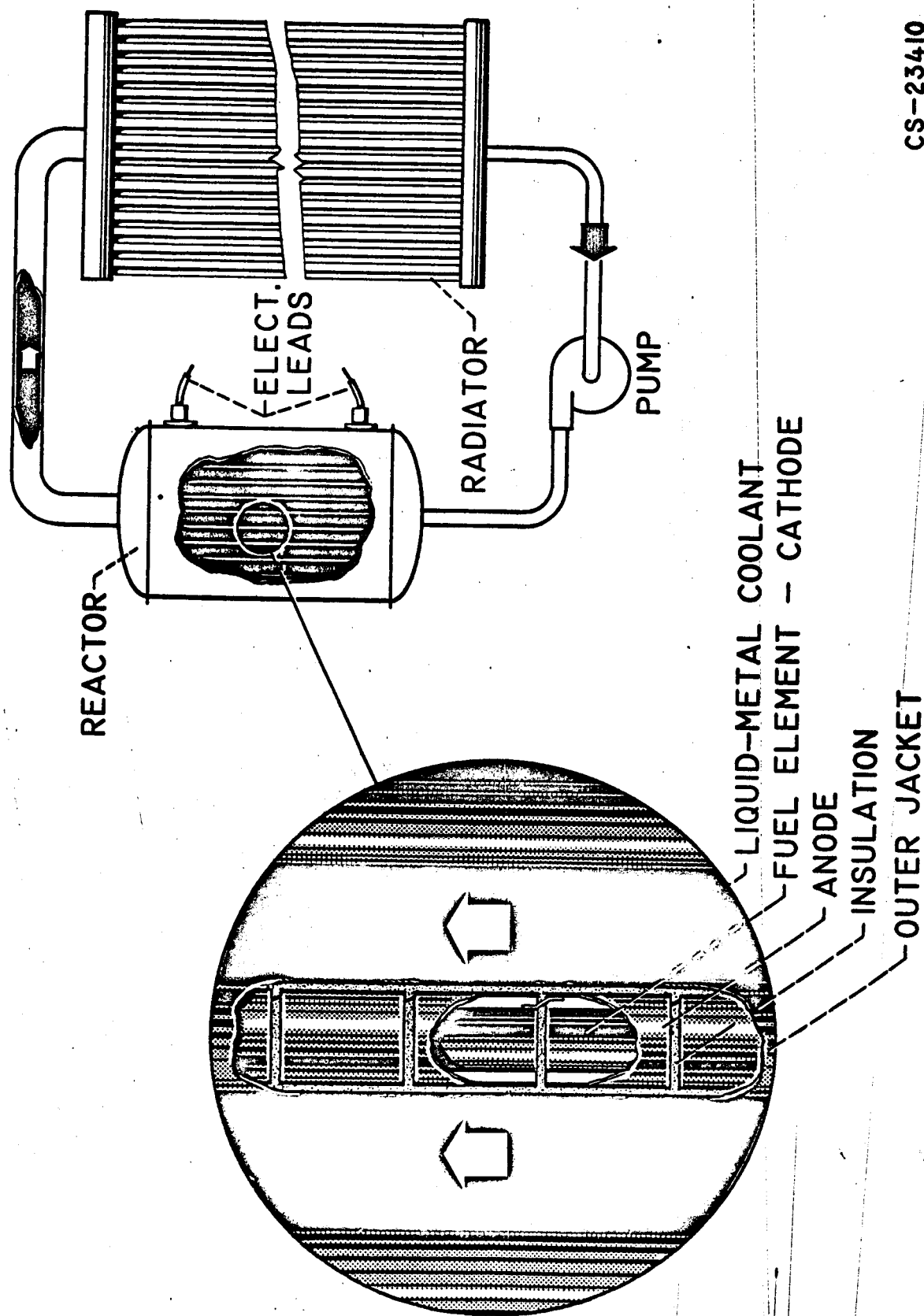
Figure 9.

# THERMIONIC CONVERTER



CS-2489

Figure 10.



CS-23410

Figure 11. - Thermionic-reactor power system.